

Introduction To Power-Frequency Electric and Magnetic Fields

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This paper introduces the reader to electric and magnetic fields, particularly those fields produced by electric power systems and other sources using frequencies in the power-frequency range. Electric fields are produced by electric charges; a magnetic field also is produced if these charges are in motion. Electric fields exert forces on other charges; if in motion, these charges will experience magnetic forces. Power-frequency electric and magnetic fields induce electric currents in conducting bodies such as living organisms. The current density vector is used to describe the distribution of current within a body. The surface of the human body is an excellent shield for power-frequency electric fields, but power-frequency magnetic fields penetrate without significant attenuation; the electric fields induced inside the body by either exposure are comparable in magnitude. Electric fields induced inside a human by most environmental electric and magnetic fields appear to be small in magnitude compared to levels naturally occurring in living tissues. Detection of such fields thus would seem to require the existence of unknown biological mechanisms. Complete characterization of a power-frequency field requires measurement of the magnitudes and electrical phases of the fundamental and harmonic amplitudes of its three vector components. Most available instrumentation measures only a small subset, or some weighted average, of these quantities. Hand-held survey meters have been used widely to measure power-frequency electric and magnetic fields. Automated data-acquisition systems have come into use more recently to make electric- and magnetic-field recordings, covering periods of hours to days, in residences and other environments. Some of these systems are portable and can be worn by individuals for personal-exposure measurements. — *Environ Health Perspect* 101(Suppl 4):73–81 (1993).

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Introduction

Terms and concepts commonly used in the discussion of power-frequency electric and magnetic fields are introduced here. The interactions of these fields with matter, particularly living tissues, also are discussed. Finally, parameters that describe power-frequency fields are listed and instruments developed to measure one or more of these parameters are described.

Electric Fields

Definition

One of the fundamental properties of the particles that make up matter is their electric charges. Electrons and protons have negative and positive charge, respectively. Experiments have shown that the magnitudes of charges carried by these two particles are equal in magnitude. Furthermore, these particles seem to possess the smallest unit of electric charge that can be isolated: No smaller charge has ever been observed, and all larger charges apparently consist of integral multiples of the electronic charge. In the Standard International (SI) system of units, the electronic charge (i.e., charge of an electron) is -1.60×10^{-19} coulombs (C).

Electrically charged particles exert forces on each other. If two particles have charges

of the opposite sign (e.g., a proton and an electron), the force between them is attractive. Otherwise, the force is repulsive. The electrical force between electrons and protons binds together the constituent particles of atoms and molecules. Electrical forces between charges are discussed using the concept of the electric field.

The electric field produced at a given point in space by a system of one or more electrically charged bodies is defined as the force that is exerted on a very small test body placed at this point and carrying a charge of exactly 1 C (Fig. 1). The electric field can be represented by an arrow that points in the direction of the electric force on the test body and whose length is in proportion to

the strength of the electric force. These arrows are called vectors and will be denoted by letters printed in boldface; the magnitude of a vector (i.e., its length) will be denoted by the same letter in normal typeface. Thus, an electric field will be denoted by E , while its magnitude will be written E .

The force, F , in units of newtons (N), on any small particle placed in an electric field is given by the equation $F = qE$, where q is the particle's charge. Note that the force on a positive charge is in the same direction as the electric field, while the force on a negative charge is in the opposite direction. By definition, the fundamental units of the electric field are force divided by charge, that is, newtons per coulomb

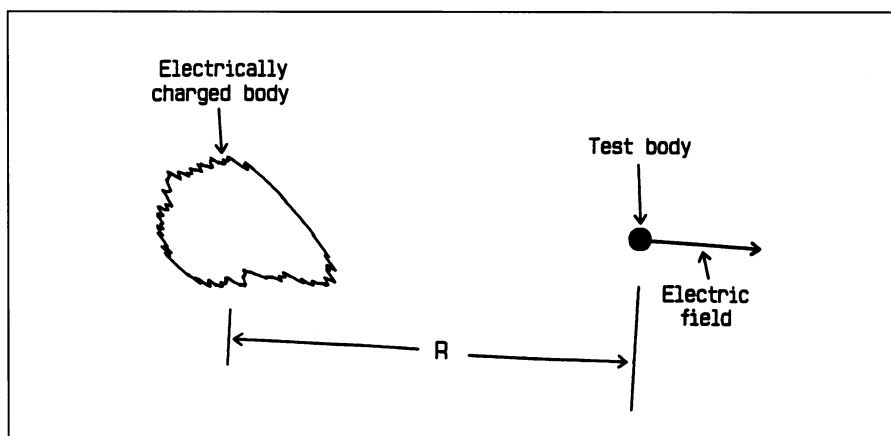


Figure 1. Electric field is force exerted on small test body carrying unit charge of 1 coulomb.

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Table 1. Terms commonly used to describe frequency ranges below 300 kHz.

Term	Frequency range
Extremely low frequency	3 Hz – 3 kHz
Power frequency	50 Hz – 1000 Hz
Very low frequency	3 kHz – 30 kHz
Low frequency	30 kHz – 300 kHz

(N/C). (As will be explained shortly, the units of volts per meter are used more commonly for electric fields.)

A second concept that is intimately related to the electric field is the electric potential. The value of the potential at a single point has no significance, but the difference in potential between two points is related directly to the physical work (i.e., force acting through a distance) the electric field will do moving an electric charge between the two points. It is interesting that potential differences generally are easier to measure than electric fields, even though their definition is more abstract. It is customary to define the potential so that the earth (i.e., ground) is at zero.

Electric potential has been given its own unit, the volt (V). However, because potential difference is defined in terms of the work done by the electric field in moving a test body between two points, it also has the units of work per unit charge, that is, force per unit charge multiplied by distance. Because the units of an electric field are force per unit charge, we see that volts = electric field \times meters. Thus, an alternative set of electric-field units is volts per meter (V/m).

Electrically conducting materials contain atoms and molecules with loosely bound electrons that can move from atom to atom under the influence of a force. Such movement, which will occur, for example, when an electric field is applied to the material, constitutes an electric current. The current passing through a specified cross-section of a body is defined as the total electric charge crossing this plane in one second. The fundamental unit of electric current is charge per unit time; in the SI system, this is given the name ampere, abbreviated A.

Often, the distribution of current within a body is of more interest than the total

current through the body. This distribution is specified using the current-density vector, J , whose direction is that of current flow at a particular point and whose magnitude is equal to $\delta I/\delta A$, where δI is the current crossing a very small surface element of area δA oriented perpendicular to J . The units of current density are amperes per square meter, or A/m². J is directly proportional to E in a wide variety of materials. That is, $J = \delta E$ (Ohm's law), where the constant of proportionality, δ , is called the electrical conductivity of the medium. The units of δ are siemens per meter (S/m).

Living tissues are electrical conductors. Conductivities of living tissues, as measured by several groups, lie in the approximate range 0.01 to 1.5 S/m (1–3). By comparison, the conductivity of copper is about 60,000,000 S/m.

Electric fields whose magnitude and direction remain constant as time passes are called static. Mathematicians have shown that any quantity that changes over time may be represented as the sum of a (possibly infinite) number of sinusoidal functions of time, each characterized by a different frequency and magnitude. The frequency of a sinusoid is the number of complete cycles it goes through in one second. The SI unit of frequency is the hertz (Hz), where 1 Hz corresponds to exactly one complete cycle in one second. Frequency ranges are often categorized by terms such as extremely low frequency, very low frequency, etc. Table 1 defines the terms used to describe the frequency ranges of interest in this report (4).

Sinusoids approximately describe the time behavior of the voltages and currents produced by the electric generators used to energize electric power systems. These generators operate at the power frequencies of 50 or 60 Hz.

Electric-Field Sources

Experiments show that a vertical, almost static, electric field exists in the lower portion of the earth's atmosphere. The source of this field is electric charge carried from the ground to the upper atmosphere by thunderstorm activity. The mean strength of

the ground-level atmospheric electric field is about 130 V/m (5). Ground-level field strengths in excess of 100 kV/m (i.e., 100,000 V/m) have been observed on flat, unobstructed surfaces during thunderstorms (5,6).

Electric fields with frequencies above about 30 Hz and extending above 100 GHz (i.e., 1×10^{11} Hz) predominantly have man-made sources. Considerable data have been published on electric fields produced by high-voltage transmission lines (7–9). Table 2 gives field intensities produced by typical power lines operating at several voltage levels (10). These data show that the largest electric fields produced at ground level by electric transmission lines now in service are about 10 kV/m. Electric fields under even higher voltage power lines that may be built in the future probably will not exceed this value significantly because of the need to limit shock hazards to personnel in the vicinity of the lines. However, as line voltages are increased, the widths of land on either side of transmission lines that are exposed to fields larger than, for example, 1 kV/m are increased. Ground-level electric fields found in substations or other electric power facilities usually do not exceed substantially the values listed in Table 2.

Work has been conducted in a number of countries to determine the actual exposures to electric fields of humans working and living in the vicinities of transmission lines and other electric-power facilities (11–16). This work has demonstrated that it is very difficult to estimate exposure using unperturbed field values (i.e., fields measured with no humans present) and simple estimates of a person's location as a function of time.

Another prominent source of electric fields in the extremely low frequency and very low frequency ranges is video display terminals (VDT). The display of information by a VDT is accomplished using a cathode ray tube (CRT). A beam of electrons, originating at the rear of a CRT, is directed onto the interior surface of its screen. The result is a spot of light at the point of impact whose intensity depends on the current in the electron beam. Magnetic fields are used to sweep the spot horizontally and vertically on the screen.

Static electric fields are produced by electrical charging of the screen of a VDT. Changes in the data being displayed by the VDT may result in modulation of these fields, usually at frequencies near 60 Hz. Finally, the circuitry used to generate the high voltages required by VDT produces electric fields at frequencies in the range of about 12 kHz to

Table 2. Typical electric and magnetic field strengths at ground level under electric-power transmission lines.

Voltage, kV	Current, A	Electric field, kV/m	Magnetic field, μ T
115	200	1.5	5.0
230	300	2.5	6.1
345	400	3.4	6.8
500	550	6.7	8.4
765	750	10.0	10.0

Table 3. Electric and magnetic fields produced 30 cm in front of video display terminals (VDT). Fields produced by VDT differ greatly, so values listed below are not characteristic of all units.

Type of field	Frequency	Value
Electric ^a	0 Hz	≤1500 V/m
Electric	ELF ^b	≤70 V/m
Electric	VLF ^c	≤3 V/m
Magnetic	ELF ^d	≤0.7 μT
Magnetic	VLF ^e	≤0.25 μT

^aOne-half hour after turn on^bExtremely low frequency range, produced by changes in data being displayed by VDT^cVery low frequency range, produced by fly-back transformer and associated circuitry^dExtremely low frequency range, produced by vertical sweep circuitry^eVery low frequency range, produced by horizontal sweep circuitry

35 kHz. Table 3 summarizes electric field data from several publications (17–19).

There are, of course, many sources of electric fields in occupational and residential settings. Bowman et al. (20) have published the results of an electric (and magnetic) field survey of electrical occupations. They found that electric-field levels in most electrical occupations were similar to those in residential environments, except for occupations such as power line workers that involved work around very high voltages. General residential electric-field measurements have been published (21). One of the stronger electric-field sources in residences is electric blankets (22).

If necessary, shielding can be used to reduce the electric fields produced by common environmental sources. Throughout the frequency range of interest to this paper, a highly effective shield can be constructed by enclosing the source of interest in practically any conducting material.

Electric-Field Coupling to Living Organisms

Exposure of a living organism to an electric field is normally specified by the unperturbed field strength, that is, the field strength measured or calculated with the subject removed from the system. The use of this field to describe exposure is convenient, because it is relatively easy to measure or calculate. But, because of field perturbations, the unperturbed field is not equal to either the electric field that actually acts on the outer surface of the body or the electric field that is induced inside the body.

Electric fields with frequencies extending from 0 Hz to well above 300 kHz are altered strongly in the vicinity of almost any conducting body, including the bodies of humans or other living organisms. This perturbation occurs because the applied field, E , induces an electric charge density on the surface of the exposed body that

generates a second electric field, E' . The total electric field is $E + E'$. Inside a conducting body, E and E' are nearly equal in magnitude but are directed oppositely. Consequently, their sum can be much smaller than either alone. In fact, for living tissues exposed to power-frequency electric fields, this cancellation is almost complete: The electric field induced inside the body is reduced relative to that outside it by at least a factor of 10,000 and, in most areas, by more than a factor of 1 million (23).

Outside the body, E and E' may add rather than cancel, so the applied field is enhanced. This enhancement tends to be greatest at the outer surface of the most sharply curved parts of the body. For example, the field at the top of the head of a person standing on the ground under a power line is enhanced by a factor of 15 to 20 (24).

Biophysical Analysis of Electric-Field Coupling

As discussed previously, the electric field acting on the surface of the body of a human or animal is enhanced over most of the body surface relative to the unperturbed electric field. Power-frequency electric fields can be perceived by humans (25) and by animals (26–28). One known mechanism of perception is hair stimulation (piloerection), that is, oscillatory hair movement by electric forces. The frequency of this vibration can be equal to or double the frequency of the applied electric field (29,30), depending on relative humidity and, possibly, other factors. Other modes of field perception have been investigated by Weigel et al. (31).

Another well-known mechanism of interaction between electric fields and biological tissues is the direct stimulation of excitable (e.g., neural) cells by the induction of voltages across their membranes sufficient to trigger their depolarizations. Such stimulation underlies the physiological

responses of perception, shock, and electrocution that result from exposure to progressively larger electric currents. Most research on this mechanism covers electric-shock hazards (32). The basic dosimetric quantity is the current density in the affected part of the body. The threshold power-frequency current density required to stimulate most excitable cells is about 10 to 20 A/m². Very long nerve cells oriented parallel to the current-density vector may be sensitive to values as small as about 1 A/m² (33–36).

It is clear that the current densities directly induced in humans or other living organisms by externally applied power-frequency electric or magnetic fields with magnitudes similar to environmental levels are much smaller than levels required to excite neural tissues. For example, Kaune and Phillips (37) estimate that the current density induced in the ankle of a human standing on one foot directly under a higher voltage electric-power transmission line could be as high as 0.04 A/m², a value only about 4% of the level needed to excite very long nerve cells.

A person standing near a higher voltage transmission line may be exposed to a substantial body current (> 0.001 A) when touching a very large conducting object such as a truck or bus (38,39). To prevent electric shock hazards, the National Electrical Safety Code (40) requires that higher voltage electric-power transmission lines be designed so that their electric fields will not induce currents exceeding 0.005 A between the body of a grounded person and a bus or large truck.

Bernhardt (35) argued that extracellular electric fields induced by external fields could not be judged safe, *a priori*, unless they were substantially weaker than the fields generated by endogenous biological processes in living tissues. This author used electrocardiographic and electroencephalographic data to estimate endogenous fields in the brain and torso and arrived at a lower limit current density of about 0.001 A/m². Bernhardt's criterion, if valid, exempts most environmental human exposures from being of concern. However, current densities exceeding Bernhardt's limit are induced in the torso of a human standing under a higher voltage transmission line (41).

Several researchers (42,43) have pointed out recently that electric potentials arising across cell membranes from intrinsic thermal charge-density fluctuations are much larger than levels induced by most environmental electric and magnetic field sources. Some argue that this means that biological effects from such exposures are impossible. However, there is now substantial amount of literature indicating that

exposure of various living organisms to power-frequency electric or magnetic fields leads to various biological responses. Living tissues apparently possess some mechanism that enables them to detect signals below the ambient cellular noise. Cooperative interaction mechanisms involving the joint response of many cells are one possibility (44–46).

Magnetic Fields

Definition

Magnetic fields, like electric fields, are produced by electric charge but only electric charge in physical motion. Magnetic fields exert forces on other charges but, again, only charges in motion. Because the most common manifestation of electric charge in motion is an electric current, it is often said that magnetic fields are produced by electric currents and interact with other electric currents.

The magnitude, F , of the force acting on an electric charge moving perpendicular to the direction of a magnetic field is equal to the product of the magnitude, v , of the particle's velocity, the magnitude of its charge, $|q|$, and the strength, B , of the field's magnetic flux density (Fig. 2), that is, $F = |q|vB$. (More generally, $F = |q|vB \sin\theta$, where θ is the angle between the directions of the velocity and the magnetic field.) Because the direction of this force is perpendicular to both the directions of the magnetic field and the particle's velocity, it can cause the particle neither to speed up nor slow down. That is, the magnetic field, by itself, can deliver no energy to a system with which it is interacting.

Time-varying magnetic fields generate electric fields through a process known as magnetic induction. The physical law that governs this phenomenon is Faraday's law. These electric fields can impart energy to a

body with which they are interacting. The electric currents induced in the body of a human exposed to a time varying magnetic field are known as eddy currents.

The complete specification of a magnetic field requires two vector quantities, the magnetic field intensity and magnetic flux density. Fortunately, these two are almost equivalent except in ferromagnetic materials such as iron. For purposes of describing human exposure, either may be used. In the SI system of units, the magnetic field intensity and flux density have units of amperes per meter (A/m) and tesla (T), respectively. The standard symbols for these two quantities are H (field intensity) and B (flux density). In vacuum, air, and to a lesser but still fully adequate approximation in nonmagnetic materials such as living tissues, $B/H = 4\pi \times 10^{-7}$.

At this time, most papers report the magnetic flux density in work related to low-frequency biological effects. A complication is that both the SI and CGS (i.e., centimeter-gram-second) systems of units have been and are still being used to report flux-density values. The CGS unit of flux density is the gauss (G), which equals exactly 0.0001 T. Magnetic flux densities found in typical residential environments have strengths of about 1 milligauss (1 mG = 0.001 G) or, equivalently, 0.1 microtesla (i.e., 0.1 μ T).

Magnetic-Field Sources

The earth produces a static magnetic field known as the geomagnetic field. The strength of this field varies from about 30 μ T (0.3 G) to 70 μ T (0.7 G). Natural phenomena, such as thunderstorms and solar activity, produce time-varying magnetic fields with frequencies in the power-frequency range (47). Such fields are usually low strength, approximately 0.01 μ T (0.1 mG). However, during intense magnetic storms (i.e., fluctuations in the earth's magnetic field resulting from solar activity), these fields can reach intensities of about 0.5 μ T (5 mG) (48).

Of greater importance, in the context of possible biological effects, are the numerous static and alternating magnetic fields arising from man-made sources. In the lowest intensity range, generally less than 0.3 μ T (3 mG), are alternating fields found in home and office environments (49,50,21). Electric blankets are one home source whose use can lead to sustained exposure to magnetic fields with somewhat elevated levels. Delpizzo (51) measured and calculated that a user would be exposed to a magnetic field produced by an Australian electric blanket of about 0.25 μ T. Because U.S. blankets

operate at lower voltage, and thus require more current, their fields are perhaps 2 to 3 times larger. Recently, electric blanket designs have been developed that produce only greatly reduced magnetic-field levels.

Higher flux densities can be produced by industrial processes using large magnets, induction motors, or heating devices. Particle accelerators use large magnets for several purposes (i.e., beam steering, momentum analysis of particles). Bowman et al. (20) recently published a survey of magnetic-field levels measured in the work areas of workers classified as electrical workers. The authors found these magnetic fields to be elevated significantly relative to those in typical residences. For example, arc welders were exposed to magnetic fields with a geometric mean of 4.1 μ T (41 mG). Lovsund and co-workers (52) documented alternating magnetic fields from 8 to 70 mT (80 to 700 G) in the steel industry in Sweden.

Significant developments in specific areas of medical care have allowed the use of very strong static and pulsed magnetic fields for various diagnostic and treatment procedures (53,54). Static and pulsed flux densities from these new technologies range from about 0.5 to 2 T (5000–20,000 G) and 1 to 10 mT (10–100 G), respectively.

Electric power lines are a common source of power-frequency magnetic fields in developed societies (55–57). Table 2 lists typical magnetic field levels produced at ground level under various classes of transmission lines. The magnetic field produced by a single long, linear current-carrying conductor decreases in magnitude in proportion to the distance from the source. Partial cancellations between the magnetic fields produced by the multiple conductors of electric power lines result in the dependence between field strength, B , and distance, R , from the source being approximately $B \propto 1/R^2$. A method was developed recently for analyzing magnetic fields produced by such sources that enables power lines with decay characteristics of $1/R^3$ or $1/R^4$ to be designed easily (58). Such lines produce substantially reduced magnetic-field levels.

Another prominent source of magnetic fields with frequencies in the extremely low frequency and very low frequency ranges is VDTs. As noted earlier, the display of information by a VDT is accomplished using a CRT. A beam of electrons, originating at the rear of a CRT, is directed onto the interior surface of the display screen, producing a spot of light at the point of impact. The intensity of this spot is related to the current in the electron beam. Magnetic fields are used to sweep the spot quickly horizontally back and

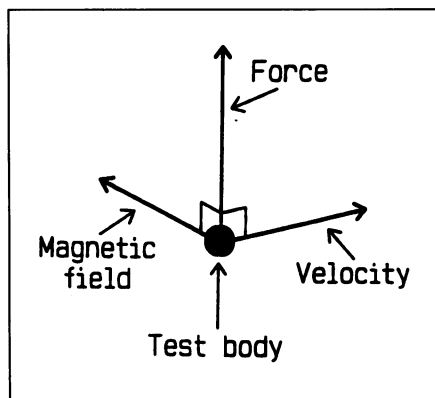


Figure 2. Force on small test body moving in a direction perpendicular to a magnetic field.

forth across the screen. (The spot is moved from left to right at a constant rate and, at the end of this sweep, is returned to the left edge very quickly.) The number of complete horizontal traversals that occurs in one second is referred to as the horizontal sweep frequency. VDTs in use have horizontal sweep frequencies ranging from about 12 to 60 kHz. Users of VDTs and others in the vicinity may be exposed to the magnetic field used to control the horizontal movement of the unit's electron beam. The spatial orientation of this leakage magnetic field tends to be vertical.

As the electron beam is swept repeatedly and horizontally across the screen of a CRT, it also is swept slowly, vertically down the screen by a second magnetic field. The vertical sweep frequencies in VDTs now in use range from about 50 to 75 Hz. This frequency is the fundamental frequency of the leakage magnetic field from the vertical sweep circuitry. The spatial orientation of this field tends to be horizontal. Table 3 summarizes published values of magnetic fields produced 30 cm from the screens of an assortment of VDTs.

In contrast to the electric field case, it is quite difficult to construct magnetic-field shields of much effectiveness for frequencies in the power-frequency range. Ferromagnetic materials can be used to construct shields, but these shields tend to be physically large, very heavy, and of limited effectiveness. Substantial thicknesses of conducting materials also can provide magnetic-field shielding. A simple rule for such shields is that their thicknesses should be large with respect to the length $712\sqrt{f\sigma}$ in meters, where f and σ are frequency (Hz) and the shield conductivity (S/m), respectively.

Magnetic-Field Coupling to Living Organisms

In contrast to electric-field exposure, the bodies of humans, animals, and other living organisms cause almost no perturbation in a power-frequency magnetic field to which they are exposed. Faraday's law of induction states that time-varying magnetic fields generate electric fields through induction. Therefore, a living organism exposed to a magnetic field also will be exposed to an induced electric field that causes currents (called eddy currents) to flow in its body. These currents circulate in closed loops that tend to lie in planes perpendicular to the direction of the magnetic field.

Biophysical Analysis of Magnetic-Field Coupling

Alternating magnetic fields induce electric fields inside the bodies of exposed humans

and animals. External alternating electric fields also induce electric fields inside bodies. The distributions of the fields induced by these two types of exposure are different, but at the level of the cell there would appear to be no fundamental difference. Thus, the biophysical analysis provided earlier in this paper for electric-field induction also can be applied to the electric fields induced by alternating magnetic fields.

How large must a magnetic field be to induce current densities sufficient to potentially stimulate excitable cells? Magnetic induction of currents can be modeled using a simple ellipsoidal approximation of a man. A typical man has a height of 1.7 m, a mass of 70 kg (59), and a body-width-to-body-thickness ratio of about two. An ellipsoid with semimajor axes of 0.85 cm, 0.20 cm, and 0.10 cm has the same body height, the same width-to-thickness ratio, and a body volume of about $7.1 \times 10^4 \text{ cm}^3$. The maximum current density, J_{max} , induced in this model when exposed to a horizontal magnetic field, B , is given by the formula

$$J_{\text{max}} = 1.2 \times 10^{-5} \sigma B f, \quad [1]$$

where the tissue conductivity, σ , has a value of 0.2 S/m and the frequency, f , is 60 Hz. As discussed earlier, a minimum current density of about 1 A/m² is required to excite long nerve cells. According to Equation 1, a whole-body magnetic field of about 0.07 T (700 G) would be required to achieve this level of induced current density. This flux density is much larger than magnetic flux densities produced by electric-power facilities. It is possible that exposures to fields of this size may occur in certain specialized industrial environments. However, these exposures normally would involve only small parts of the body and, thus, would not result in the induction of current densities as large as the values calculated with Equation 1 for whole-body exposures.

In addition to the induction, magnetic fields exert forces on charged particles that are in motion within a living organism. The most prevalent types of motion in matter are the motion of electrons in atoms, nucleons in nuclei, and the intrinsic spins of these particles. These motions lead to the existence of magnetic dipole moments that may be either permanent or induced by the applied magnetic field. A magnetic dipole in a magnetic field experiences a torque that attempts to align it parallel to the applied field. However, this alignment is resisted by random thermal motion and a statistical distribution of dipole directions is thereby established.

The alignment of a dipole with a magnetic field can be calculated (54,60). At body temperature (37°C) and at a magnetic flux density of about 30 μT (0.3 G) that is characteristic of a heavily loaded transmission line, alignment is less than about 10^{-8} for electronic and nuclear magnetic moments that might occur in living tissues. Obviously, the effect on the magnetic dipoles that are part of the body of a subject exposed to such a magnetic field is very small. Of course, every single dipole is subject to this effect and, conceivably, some sort of process might exist that is sensitive to the average response of a large number of dipoles.

Charged particles also are carried by the bulk motion of various parts of the body. For example, charged ions are carried by blood flow. These ions are both positively and negatively charged and will experience magnetic forces in opposite directions, resulting in a separation of the two polarities of electric charge and, therefore, in the generation of electric potentials. These potentials can produce artifacts in the electrocardiograms of rats (61) exposed to static magnetic fields with flux densities above 0.3 T (3000 G).

One proposed mechanism of interaction between ac magnetic fields and living organisms is ion cyclotron resonance (62). There are several versions of this mechanism. The simplest proposes that there is an interaction between applied alternating and static magnetic fields that may cause a biological response if the frequency, f , of the ac field is close to the cyclotron resonance frequency, f_c , defined by the equation

$$f_c = \frac{1}{2\pi} \left(\frac{q}{m} \right) B_o, \quad [2]$$

where q and m are the charge and mass of a biological ion of interest and B_o is the strength of the static magnetic field. In most situations, the static field is just the earth's magnetic field, which varies in flux density from about 30 to 70 μT over the surface of the earth. (Values outside this range can be found in the vicinity of ferromagnetic materials, such as those used in the construction of larger buildings.)

The name ion cyclotron resonance stems from the fact that a charged particle, such as an ion, traveling in a vacuum perpendicular to a static magnetic field will follow a circular path and will make f_c complete orbits in 1 sec. However, because ions in living tissues are not traveling in a vacuum but are, instead, moving through a highly viscous medium, attempts to apply this interaction picture have not been successful. However,

Table 4. Cyclotron resonance frequencies (Hz) for ions of biological interest and for static magnetic flux densities characteristic of various locations on the surface of earth.

Ion	Static magnetic flux density		
	30 μ T	50 μ T	70 μ T
Li ⁺	66	111	155
Na ⁺	20	33	47
Mg ²⁺	38	63	88
Cl ⁻	13	22	30
K ⁺	12	20	27
Ca ²⁺	23	38	54

empirically, Equation 2 does describe certain behaviors of several biological systems (62).

Table 4 lists cyclotron resonance frequencies for a number of ions of biological interest and for static magnetic flux densities characteristic of those found on the surface of the earth. Note that the resonant frequencies of certain ions (Li⁺, Mg²⁺, Ca²⁺) are near the power-line frequencies of 50 or 60 Hz at some locations on the earth.

Characterizing Power-Frequency Fields

This section describes methods for characterizing power-frequency electric and magnetic fields, and it describes several instruments that have been developed for this purpose.

Quantities Characterizing Power-Frequency Fields

Power frequency fields (either electric or magnetic) are vectors and therefore have lengths (magnitudes) and directions. Vectors can be decomposed into three orthogonal components that are usually labeled the x , y , and z components. Thus, three numbers (three measurements) are needed to characterize fully a field at any instant in time. However, fields of interest to this paper usually are not constant in time.

The next simplest case is when each component of a power-frequency field is a sinusoidal function of time: $B_k(t) = M_k \sin(2\pi ft + \phi_k)$, where the index k denotes the vector component (i.e., x , y , or z) under discussion, M_k is the peak magnitude of this component, f is the field's frequency, t is time, and ϕ is the phase angle of this component. Assuming the frequency is known, measurement of two parameters (M_k and ϕ) are needed to characterize each component of a power-frequency field.

Field magnitudes are almost always expressed in terms of root-mean-square (RMS) values rather than peak values. The relationship between these two values is $(M_{rms})_k = M_k/\sqrt{2}$. An RMS value can sometimes be interpreted as a measure of the time-averaged energy associated with the magnetic field.

Generally, the actual value of the phase angle of any component of a vector field is of no particular significance, but the relative phase angles between components are important. To see this, consider a field that has only nonzero x and y components. First, suppose that the x and y components are in phase (i.e., $\phi_x = \phi_y$). The two components' time behaviors will mimic each other: They will pass through zero at the same time, will reach their maximum values at the same time, and so on. This behavior is shown in the left side of Figure 3. It is not hard to see that, as time proceeds, the tip of the magnetic field vector will trace out a straight line that passes through the origin (Fig. 3). Accordingly, this state is referred to as linear polarization.

In the second case, assume the relative phase angle between the two components is 90°. Then, as shown in the right side of Figure 3, the time behaviors of the two components will be out of step. As one component reaches its maximum value, the other will pass through zero, and vice versa. Because the two components are never simultaneously zero, the total magnetic field always is different from zero. Figure 3 shows the elliptical path that the tip of the magnetic

field vector follows as a function of time. This condition is given the name elliptical polarization. If the peak (or, equivalently, RMS) magnitudes of the x and y components are equal, the ellipse becomes a circle, and we have the limiting case of circular polarization.

The complete specification of a sinusoidal vector field thus requires the measurement of five quantities, three magnitudes, and two relative phase angles. Unfortunately, the situation often is more complicated because the power-frequency magnetic fields under study are distorted from pure sinusoids. Because this distortion tends to be the same, cycle after cycle, each component of a power-frequency field can be viewed as the sum of many different sinusoids, with the frequency of each successive term in this series being equal to the next larger integral multiple of the power frequency (50 or 60 Hz). That is,

$$B_k = M_{k1} \sin[2\pi(f)t + \phi_{k1}] + M_{k2} \sin[2\pi(2f)t + \phi_{k2}] + M_{k3} \sin[2\pi(3f)t + \phi_{k3}] + \dots \quad [3]$$

The first term in this series, which involves just the power-frequency, is called the fundamental, and the terms involving integral multiples of this frequency are called harmonics. The second (third, fourth, ...) harmonic is the term whose frequency is 2 (3, 4, ...) times the power frequency.

Clearly, complete characterization of a power-frequency magnetic field is a formidable task requiring very sophisticated instrumentation. Instead, most instruments measure some average of the parameters that fully describe a power-frequency field.

The simplest type of meter responds only to the component of an electric or

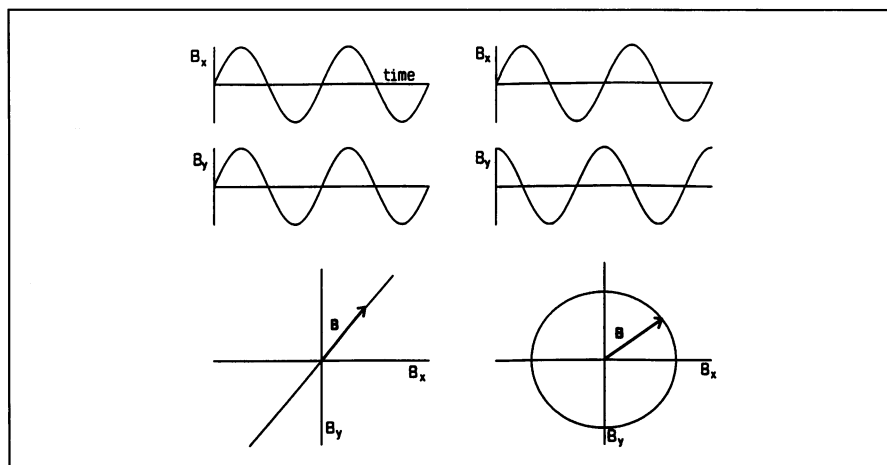


Figure 3. Left and right sides of figure show temporal and spatial patterns of components of linearly and circularly polarized vectors, respectively.

magnetic field that is parallel to the axis of the meter's probe. While some meters are designed to respond only to the 60-Hz fundamental, by using filters to reject all the terms in Equation 3 except the first, it is more common for a meter to accept a range of frequencies extending from about 30 to 40 Hz to a few hundred to a few thousand hertz. These latter meters have come to be referred to as broad-band instruments.

There are several ways to characterize the magnitude of a harmonically distorted signal. Some meters, known as average-responding meters, measure the average over a few cycles of the absolute value of the signal under study. Other meters measure the rms magnitude. Average responding meters are calibrated to display RMS values but do so without error only if there are no harmonics present.

There are several ways that a single-axis field meter, such as described in the preceding paragraph, can be used to characterize a three-dimensional electric or magnetic field. In one approach, the probe of the meter would be oriented in space to obtain the largest reading possible. This value is called the maximum field strength. Alternatively, the probe can be oriented in three perpendicular directions to measure the x , y , and z components of field strength. Then, a measure of the total field strength called the resultant field can be calculated using the formula

$$B = \sqrt{B_x^2 + B_y^2 + B_z^2} \quad [4]$$

The maximum and resultant values are the same for linearly polarized fields. Otherwise, the resultant is always larger. In the extreme case of circular polarization, the resultant is 41% larger than the maximum value.

Survey Field Meters

A survey meter is a handheld instrument used to measure the electric or magnetic field at a particular point. The value so measured is displayed using either an analog or a digital display. Survey meters have no memory

capability. Thus, any values that are to be retained must be written down by the user.

An interesting feature of some commercial meters is that their frequency responses can be set to be either flat or linear. With a flat response, all fields within the instrument's bandwidth are weighted equally. For example, a $0.1 \mu\text{T}$ (1 mG) magnetic field would be measured as $0.1 \mu\text{T}$ no matter what its frequency (as long as it was in the meter's bandwidth). With a linear response, this same field would be measured as $0.1 \mu\text{T}$ if its frequency were 60 Hz and $1.0 \mu\text{T}$ if its frequency were 600 Hz. By measuring with both bandwidths, qualitative information can be obtained about the harmonic distortion of the field under study.

Automated Data Acquisition Systems

Automated data acquisition systems are designed to be placed to acquire electric- or magnetic-field data for extended periods of time. The first system that was used in homes (21) was very large and consisted of several units that had to be wired together. Recent systems are much more sophisticated and can be used to characterize fully the magnitudes and phases of the fundamental and harmonics of all three vector components of the electric or magnetic field under study (63).

Personal Exposure Meters

Personal exposure meters can measure electric and/or magnetic fields while being worn by an individual. They therefore must be battery powered, small, and of low weight. The most powerful personal exposure meters available at this time essentially are battery-powered portable data acquisition systems. These meters incorporate on-board microcomputers and can be linked to other computers for the transfer of data.

Summary


An electrically charged particle exposed to an electric and a magnetic field will experience a force on it. If the particle is at rest, this force will be due to the electric field. Otherwise, both electric and magnetic forces will be

present. All the electrically charged particles in living tissues will experience forces when exposed to electric and/or magnetic fields. Because living tissues are conductors, these forces will cause electric currents to flow.

Electric fields are specified by their field strengths in volts per meter (V/m). In the power-frequency region, magnetic fields are specified most often by their flux densities in units of tesla or gauss.

Static electric and magnetic fields are produced by the earth. In addition, very low levels of these fields are produced naturally with frequencies in the power-frequency range (i.e., 50–1000 Hz). Much stronger electric and magnetic fields are a byproduct of human use of electric power. The strengths of the electric and magnetic fields found in typical residences in developed countries lie in the approximate ranges of 0 to 10 V/m and 0 to $1 \mu\text{T}$ (0–10 mG), respectively. Electric and magnetic fields under high-voltage electric power transmission lines can reach levels as high as 10,000 V/m and $30 \mu\text{T}$, respectively. Even stronger magnetic fields can be found in certain occupational environments.

Because the body of a person is a good conductor at power frequencies, its interior is shielded strongly from electric fields. The electric field induced inside most parts of the body by an external electric field is reduced by at least a factor of 1 million. This field is too small to excite nerve cells and is, apparently, considerably smaller than fields that naturally occur in tissues. Biological effects caused by such fields must be due to mechanisms of interaction not yet understood.

In contrast to electric-field exposure, power-frequency magnetic fields penetrate living tissues without significant perturbation and induce circulating electric fields and currents in the body of an exposed human. The sizes of these induced electric fields are similar to those induced by electric-field exposure. Moving particles within the body also will interact directly with the applied magnetic field, but the strength of this interaction is small relative to thermal interactions. 

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